Conductivity of Silicon Inversion Layers: comparison with and without in-plane magnetic field.

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(February 2, 2008)

A detailed comparison is presented of the temperature dependence of the conductivity of dilute, strongly interacting electrons in two-dimensional silicon inversion layers in the metallic regime in the presence and in the absence of a magnetic field. We show explicitly and quantitatively that a magnetic field applied parallel to the plane of the electrons reduces the slope of the conductivity versus temperature curves to near zero over a broad range of electron densities extending from n_c to deep in the metallic regime where the high field conductivity is on the order of $10e^2/h$. The strong suppression (or "quenching") of the metallic behavior by a magnetic field sets an important constraint on theory.

PACS numbers: 71.30.+h, 73.40.Qv, 73.50.Jt

The conductivity of low density, strongly interacting electrons (or holes) in two dimensions increases with decreasing temperature above a critical electron density n_c (or hole density p_c), raising the possibility that there exists an unexpected metallic phase and a metal-insulator transition in two dimensions [1]. This behavior has been observed in many different 2D systems and is particularly pronounced in inversion layers in silicon MOSFET's. The application of a magnetic field parallel to the plane of the electrons (or holes) has a dramatic effect, causing the conductivity to change by many orders of magnitude at low temperatures and low densities near n_c (p_c). In silicon MOSFET's, the conductivity decreases as the magnetic field is increased and then saturates to a value that is approximately constant [2,3]. Other systems exhibit very similar behavior, with a conductivity that reaches a knee and then continues to decrease but with much smaller slope [4]. Shubnikov-deHaas experiments have been performed that indicate that the electrons become fully polarized at or near the value of in-plane magnetic field that causes the saturation or knee observed in the magnetoconductivity [5–7]. These intriguing and quite anomalous effects have been the subject of a great deal of interest and debate.

Although a number of studies have shown qualitatively that a magnetic field decreases the conductivity and suppresses the metallic behavior [2,8–10], there has been no systematic investigation of the temperature dependence in moderate and high magnetic field. The purpose of the present note is to demonstrate explicitly and quantitatively that the application of a magnetic field parallel to the plane of the electrons in silicon inversion layers sharply reduces the temperature dependence of the conductivity over a broad range extending to electron densities deep in the metallic regime where the conductivity at high field is on the order of $10e^2/h$.

Data are presented for three silicon MOSFETs with mobilities μ at 4.2 K of $\approx 30,000$ V/(cm^2s) (sample #1) and $20,000$ V/(cm^2s) (samples #2 and #3). Contact resistances were minimized by using a split-gate geometry, which allows a higher electron density in the vicinity of the contacts than in the 2D system under investigation. The resistance was measured in a ^{3}He Oxford Heliox system as a function of temperature in zero field and in a parallel field of 10 Tesla by standard four-probe AC techniques using currents in the linear regime, typically below $5nA$, at frequency 3Hz. Metallic temperature dependence was found in zero field for all samples at electron densities above $n_c \approx 0.9 \times 10^{11}$ cm^{-2}.

The conductivity of a silicon MOSFET sample in the absence of magnetic field is shown as a function of temperature for eight different electron densities in Fig. 1(A); Fig. 1(B) shows the conductivity for the same electron densities in a magnetic field of 10 Tesla applied parallel to the electron plane. The temperature dependence in the absence of a field is strongly suppressed by an in-plane magnetic field of 10 T. Similar results were obtained for the two other samples studied. It should be noted that the conductivity is near or at its high-field, saturated value in 10 T for all the densities shown.

In order to demonstrate the effect of high in-plane magnetic fields, we determined the slope of the conductivity curves $d\sigma/dT$ in zero field and in high magnetic field; this is illustrated in Fig. 2 for two different electron densities.

We now examine how the temperature dependence of the conductivity evolves as the magnetic field is increased from zero to a value high enough that the conductivity has reached its high-field saturated value where the elec-

tron spins are completely aligned. For a constant electron density $n = 1.64 \times 10^{11}$ cm^{-2}, the closed symbols of Fig. 3 are the slopes $d\sigma(H)/dT$ of the σ versus T curves for several values of in-plane magnetic field. Although the σ versus T curves at finite field exhibit some detailed structure [11], these are small effects that do not affect the over-all behavior in a substantial way. For comparison, the open symbols in Fig. 3 denote the difference $[\sigma(1.35K) - \sigma(0.27K)]$; the main features of the curve are unaltered. The (negative) slope changes rapidly with increasing in-plane magnetic field and assymptotically approaches a value near zero as the field approaches the value required to saturate the conductivity and align the spins.

range of electron densities deep into the metallic phase, where the conductivity is 10 to 20 times the quantum unit of conductance. Figure 4 shows the ratio of the slope in a high in-plane field of 10 T to the slope in zero field, $\frac{d\sigma(H=10T)/dT}{d\sigma(0)/dT}$, plotted as a function electron density. As indicated by the dashed horizontal lines, the ratio does not exceed ± 0.1 and is near zero over the entire range of densities studied, from $n = 0.95\times 10^{11}$ cm^{-2} to 2.5×10^{11} cm^{-2}. The temperature dependence in high in-plane magnetic field exhibits some scatter. It is weak but finite, and it is positive or negative depending on electron density. We attribute this to remanent, weak effects that become dominant when the field has suppressed the strong zero-field dependence on temperature.

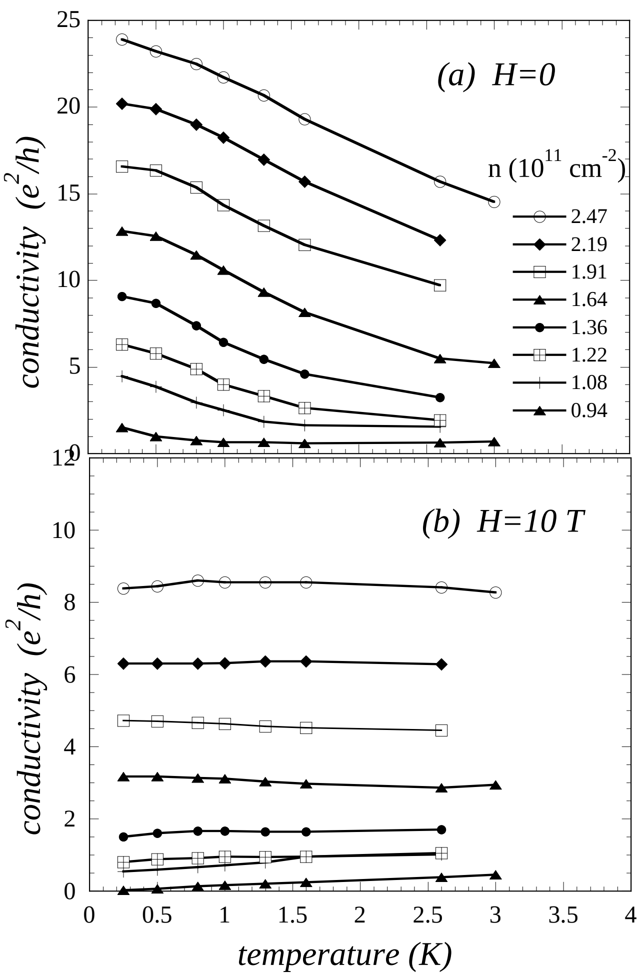

FIG. 1. Conductivity of silicon MOSFET sample #2 as a function of temperature for different electron densities, as labelled: (A) in the absence of external magnetic field; (B) in a field of 10 T applied parallel to the plane. Similar results were obtained for samples #1 and #3.

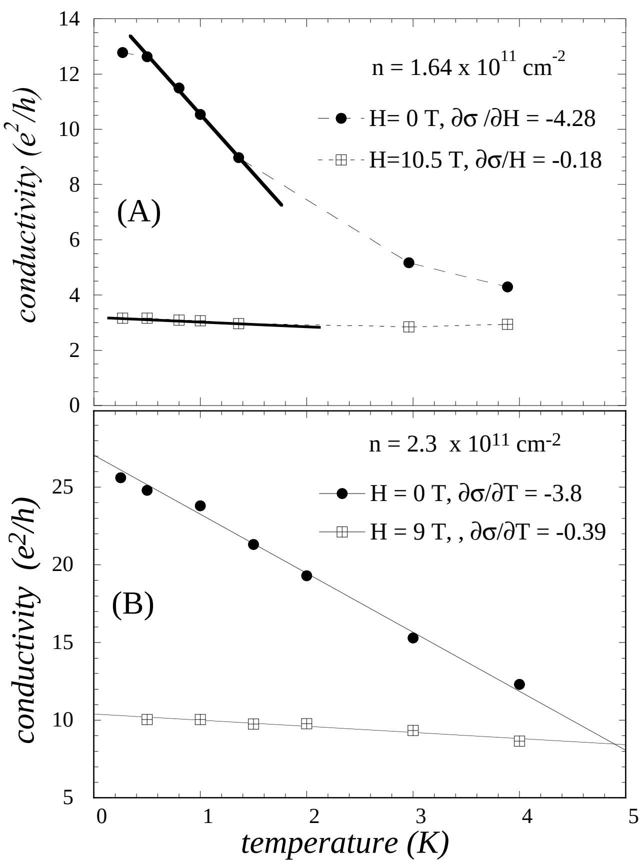

FIG. 2. For two electron densities, the lines illustrate the procedure used to determine the slope $d\sigma/dT$ plotted in Fig. 4. Note that the range over which the slope is approximately constant broadens as the electron density is increased. Data shown for sample #3.

The behavior illustrated in Fig. 3 obtains over a broad

Many theories have been proposed to account for the interesting behavior of two-dimensional systems of electrons such as silicon MOSFET's. Temperature-dependent screening in a Fermi gas has been suggested

by many [12] as the source of the temperature dependence of the conductivity. A recent theory of Zala, Narozhny and Aleiner [13], which considers exchange as well as Hartree terms, provides sufficient detail to allow

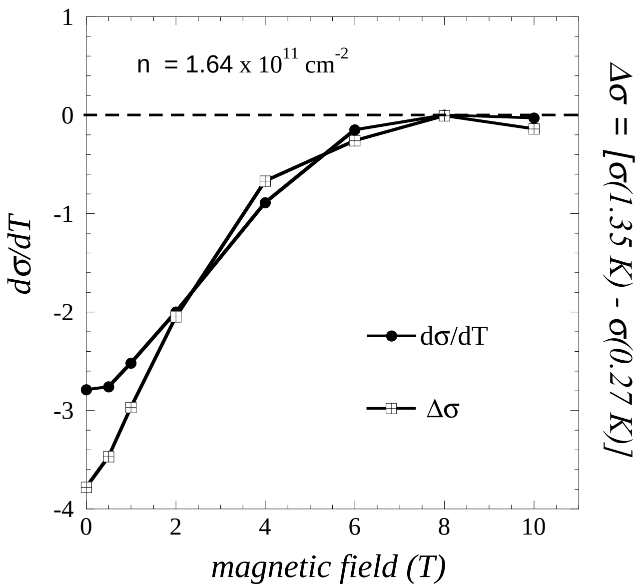

FIG. 3. Closed symbols denote the slope $d\sigma/dT$ versus in-plane magnetic field H for silicon MOSFET sample #2 at electron density 1.64×10^{11} cm^{-2}. Open symbols denote the difference in conductivity $[\sigma(1.37K) - \sigma(0.27K)]$.

comparison with experiment. Within this theory, the ratio plotted in Fig. 4 can be expressed in term of the Fermi liquid parameter F_0^σ:

$$r = \frac{d\sigma(H)/dT}{d\sigma(0)/dT} = \frac{1 + [3F_0^\sigma/(1+F_0^\sigma)]}{1 + [15F_0^\sigma/(1+F_0^\sigma)]}.$$

The inset to Fig. 4 shows a plot of the ratio $r = [(d\sigma(H)/dT)/(d\sigma(0)/dT)]$ plotted as a function of the Fermi liquid parameter F_0^σ.

Direct comparisons of the temperature and field dependence of the conductivity with the theory of Zala *et al.* have yielded a range of values for the Fermi liquid parameter F_0^σ. Vitkalov $etal$. [14] obtained $F_0^\sigma = -0.15$ for electron densities between 1.6×10^{11} cm^{-2} and 3.3×10^{11} cm^{-2}. Examination of the inset to Fig. 4 shows that this is inconsistent with the ratios between 0.1 and -0.1 found experimentally. A value near $F_0^\sigma = -0.5$ obtained in this range of densities by Pudalov $etal$. [15] is marginally outside the bounds shown in Fig. 4, while $F_0^\sigma \approx -0.3$ reported by Shashkin *et al.* [16] falls between the required bounds.

A number of other theoretical scenarios have been advanced, including percolation in an inhomogeneous system composed of metallic and insulating regions, a Wigner crystal or glass, ferromagnetism, superconductivity, a spin glass, an electron glass [1]. Complete suppression of the zero-field temperature dependence by in-plane magnetic field is predicted by the theory of Spivak and Kivelson [17], which considers phase separation and intermediate phases between the Fermi liquid and the Wigner crystal.

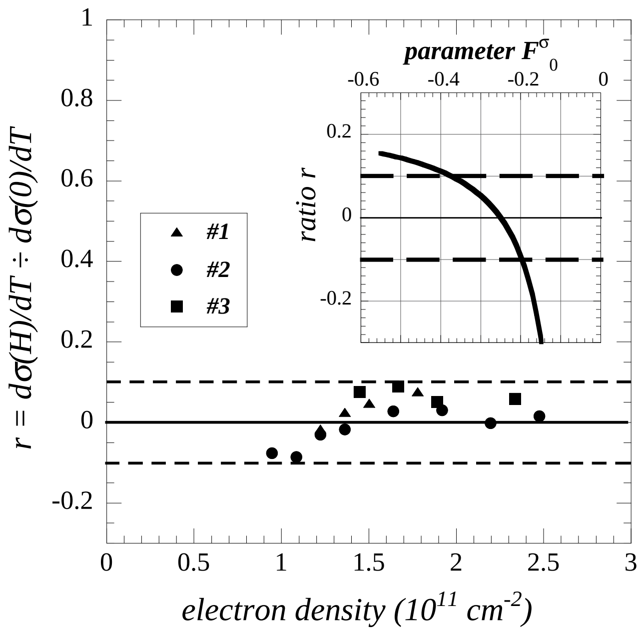

FIG. 4. The ratio $r = \frac{d\sigma(H)/dT}{d\sigma(0)/dT}$ versus electron density for three samples, as labelled. The inset shows r versus the Fermi liquid parameter F_0^σ predicted by the theory of Zala *et al.* [13].

In summary, data are reported for inversion layers in high mobility silicon MOSFET's that demonstrate that an in-plane magnetic field suppresses the metallic temperature dependence of the conductivity observed in the absence of magnetic field. The metallic behavior is strongly suppressed (or "quenched") over a broad range of densities extending from n_c upward deep into the metallic regime where the high field conductivity is 10 times the quantum unit of conductivity. This is a robust and central feature of these two-dimensional systems that sets an important constraint on theory.

We thank Boris Spivak and Steve Kivelson for stimulating this paper and for numerous discussions. This work was supported by DOE-FG02-84-ER45153 and NSF grant DMR-0129581.

[1] For reviews, see E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys. **73**, 251 (2001); S. V. Kravchenko and M. P. Sarachik, Rep. Prog. Phys. **67**, 1 (2004); V. M. Pudalov, preprint cond-mat/0405315 (2004); A. A. Shashkin, preprint cond-mat/0405556 (2004).

[2] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. **79**, 2304 (1997).

[3] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, Pis'ma Zh. Eksp. Teor Fiz. **65**, 887 (1997) [JEPT Lett. **65**, 932 (1997)].

[4] J. Yoon, C. C. Li, D. Shahar, D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. **84**, 4421 (2000); R. Pillarisetty, Hwayong Noh, E. Tutuc, E. P. De Poortere. D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. **90**, 226801 (2003).

[5] T. Okamoto, K. Hosaya, S. Kawaji, and A. Yagi, Phys. Rev. Lett. **82**, 3875 (1999).

[6] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. Lett. **85**, 2164 (2000); S. A. Vitkalov, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. **B 64**, 073101 (2000).

[7] E. Tutuc, E. P. De Poortere. S. J. Papadakis, and M. Shayegan, Phys. Rev. Lett. **86**, 2858 (2001).

[8] V. T. Dolgopolov, G. V. Kravchenko, A. A. Shashkin, and S. V. Kravchenko, JEPT Lett. **55**, 733 (1992).

[9] K. M. Mertes, H. Zheng, S. A. Vitkalov, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. B **63** R041101 (2001).

[10] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. Lett. **87**, 266402 (2001).

[11] Yeekin Tsui, S. A. Vitkalov, and M. P. Sarachik, unpublished.

[12] See, for examples, T. Ando, A. B. Fowler, and F. Stern Rev. Mod. Phys. **54**, 437 (1982); S. Das Sarma, Phys. Rev. B bf 33, 5401 (1986); A. Gold and V. T. Dolgopolov, Phys. Rev. B **33**, 1076 (1986); S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **83**, 164 (1999);I. F. Herbut, Phys. Rev. B **63**, 113102 (2001).

[13] G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B **64**, 214204 (2001); G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B **65**, 020201(R) (2002).

[14] S. A. Vitkalov, K. James, B. N. Narozhny, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. B **67**, 113310 (2003).

[15] V. M. Pudalov, M. E. Gershenson, H. Kojima, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **91**, 126403 (2003).

[16] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. **B 66**, 073303 (2002).

[17] B. Spivak, Phys. Rev. B **67**, 125205 (2002); B. Spivak and S. A. Kivelson, preprint cond-mat/0310712 (2003).